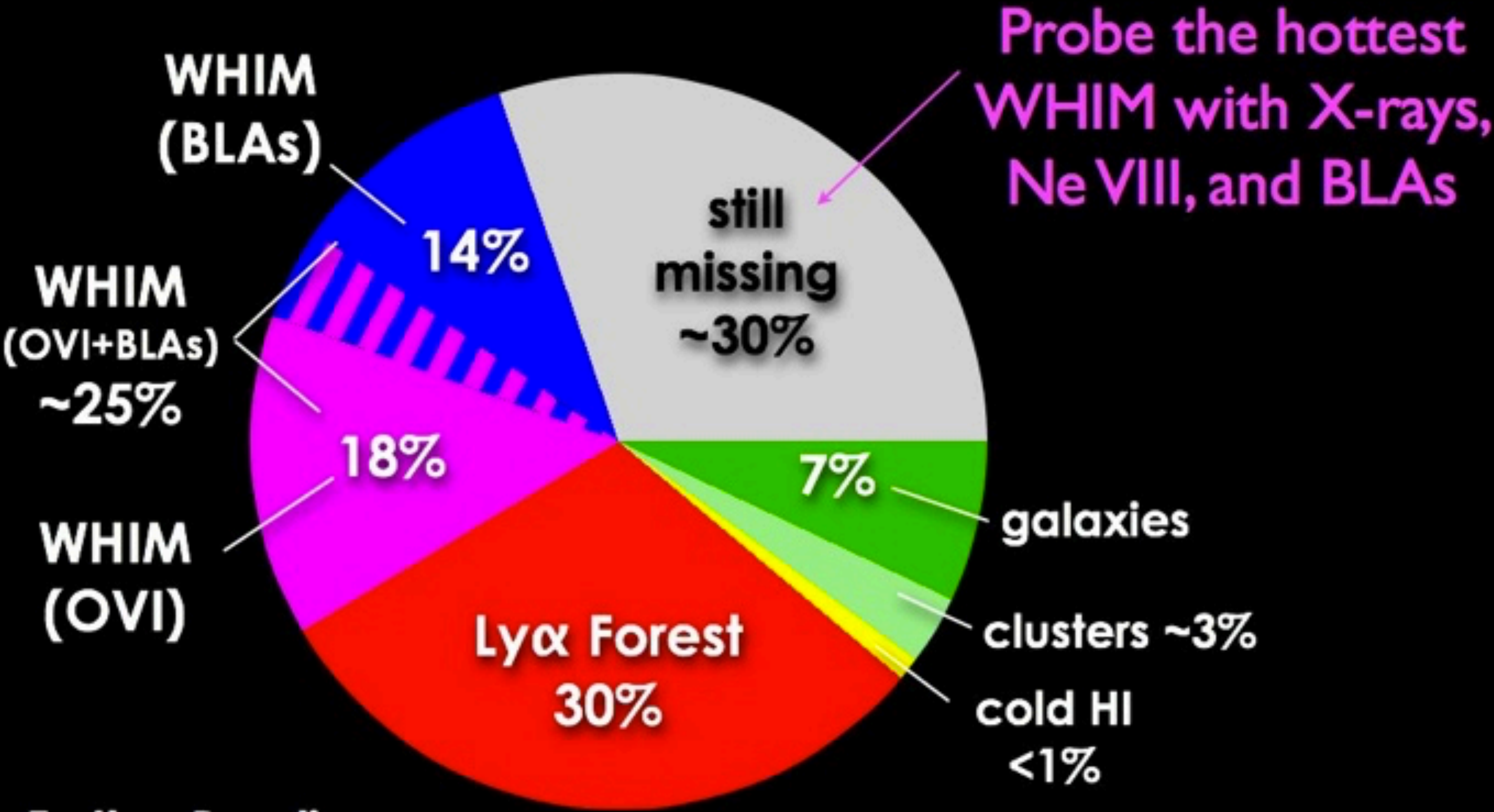
Observing the Warm and Hot Baryons at Low Redshift

Taotao Fang
Xiamen University

Wien, Österreich
2018.8.30

Low-z Baryon Census - 2011



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Shull+2011

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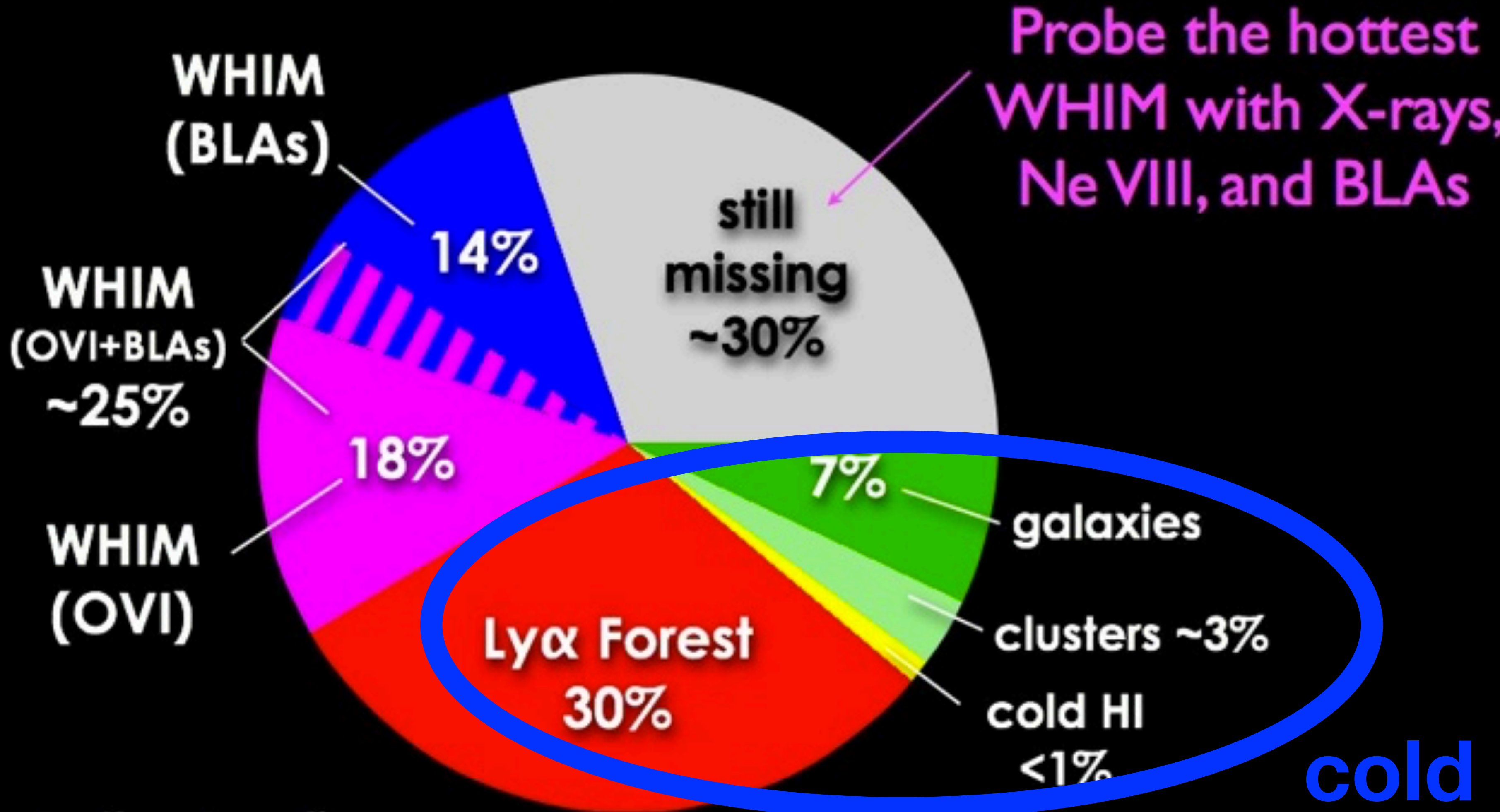

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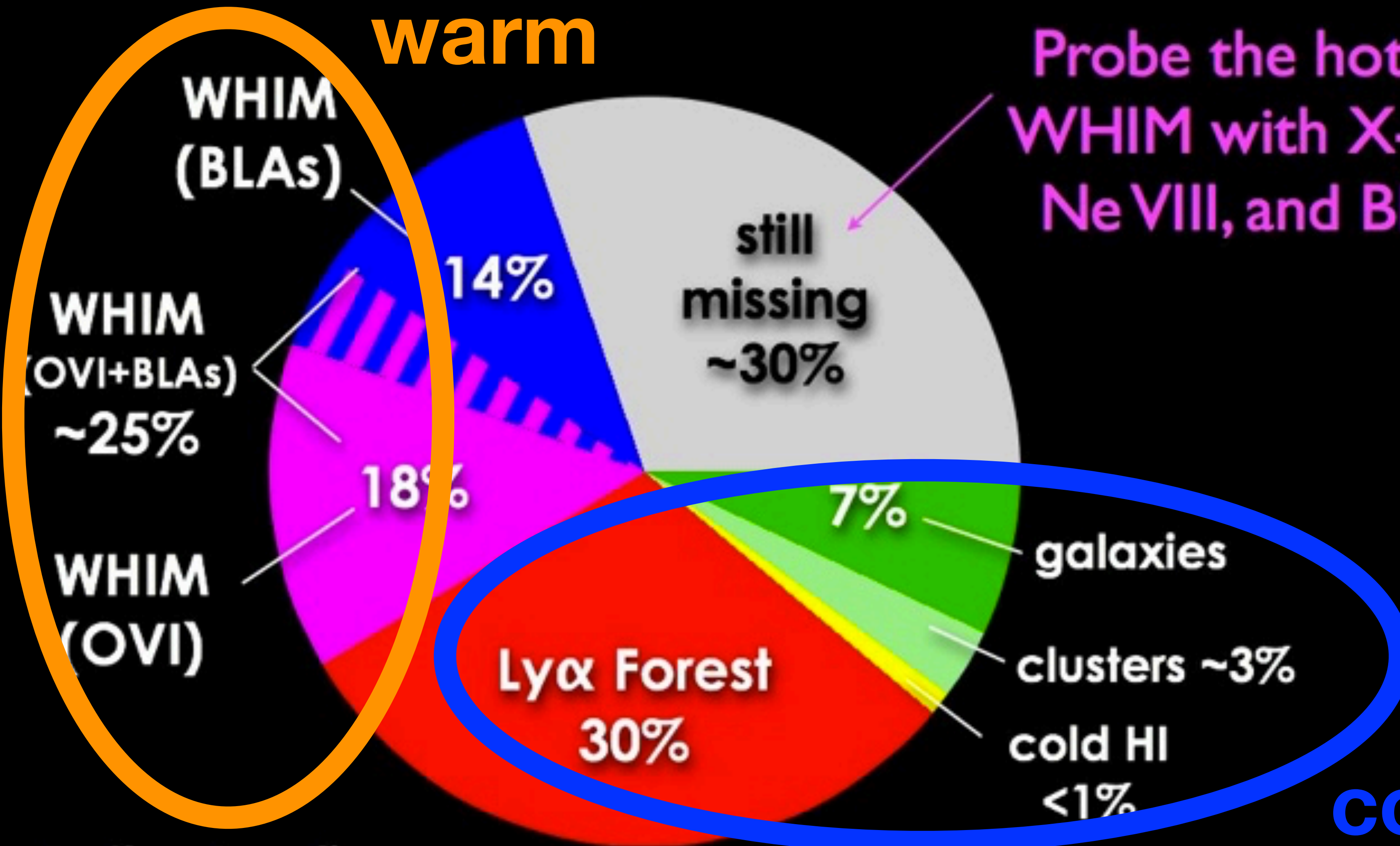

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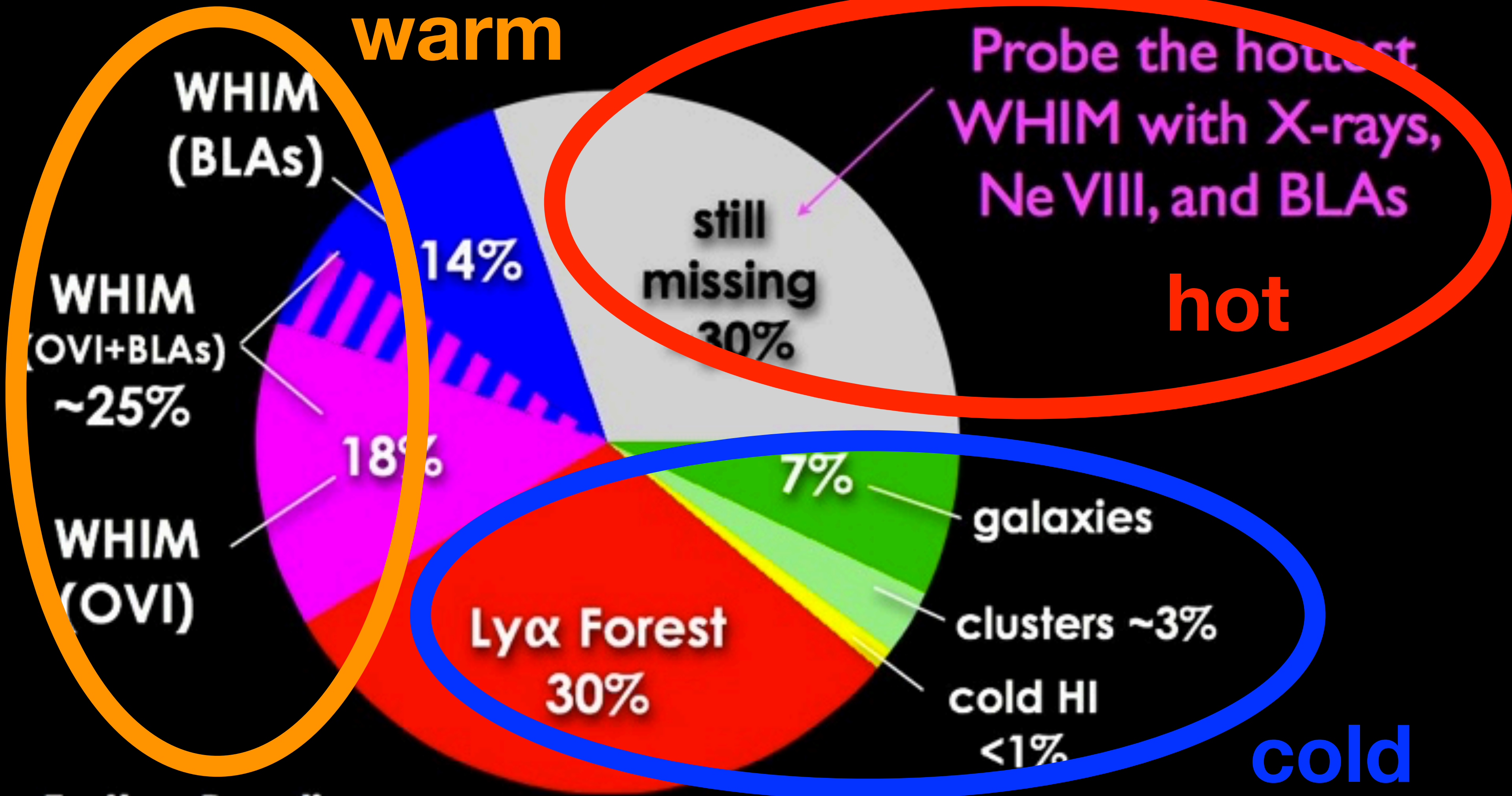

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How to detect the warm/hot baryons: UV/X-ray spectroscopy

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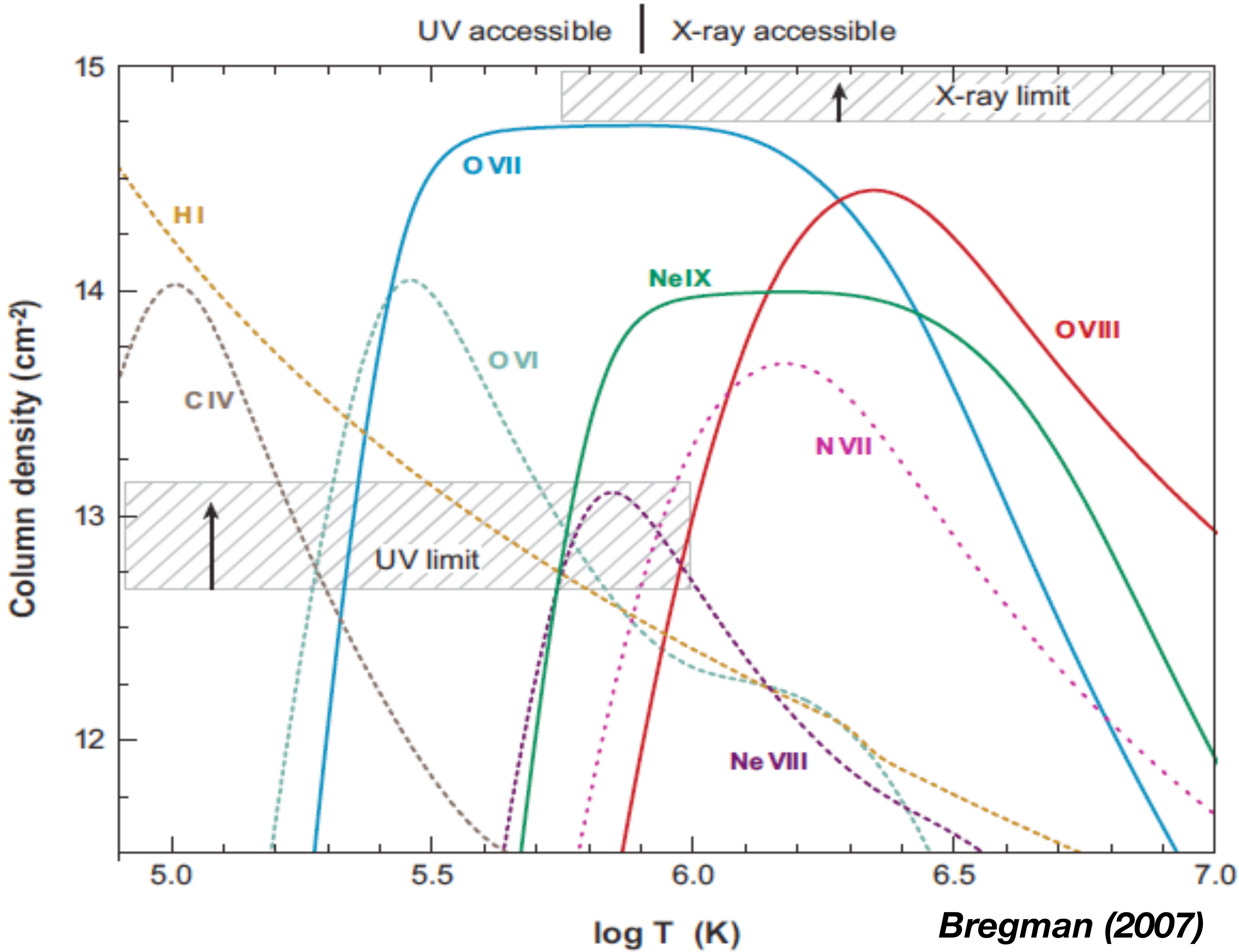
Absorption	*Imaging*
Depend on background sources	No dependency on background sources
Sensitive to density	Sensitive to density square
No dependency on the XRB	Removal of the XRB

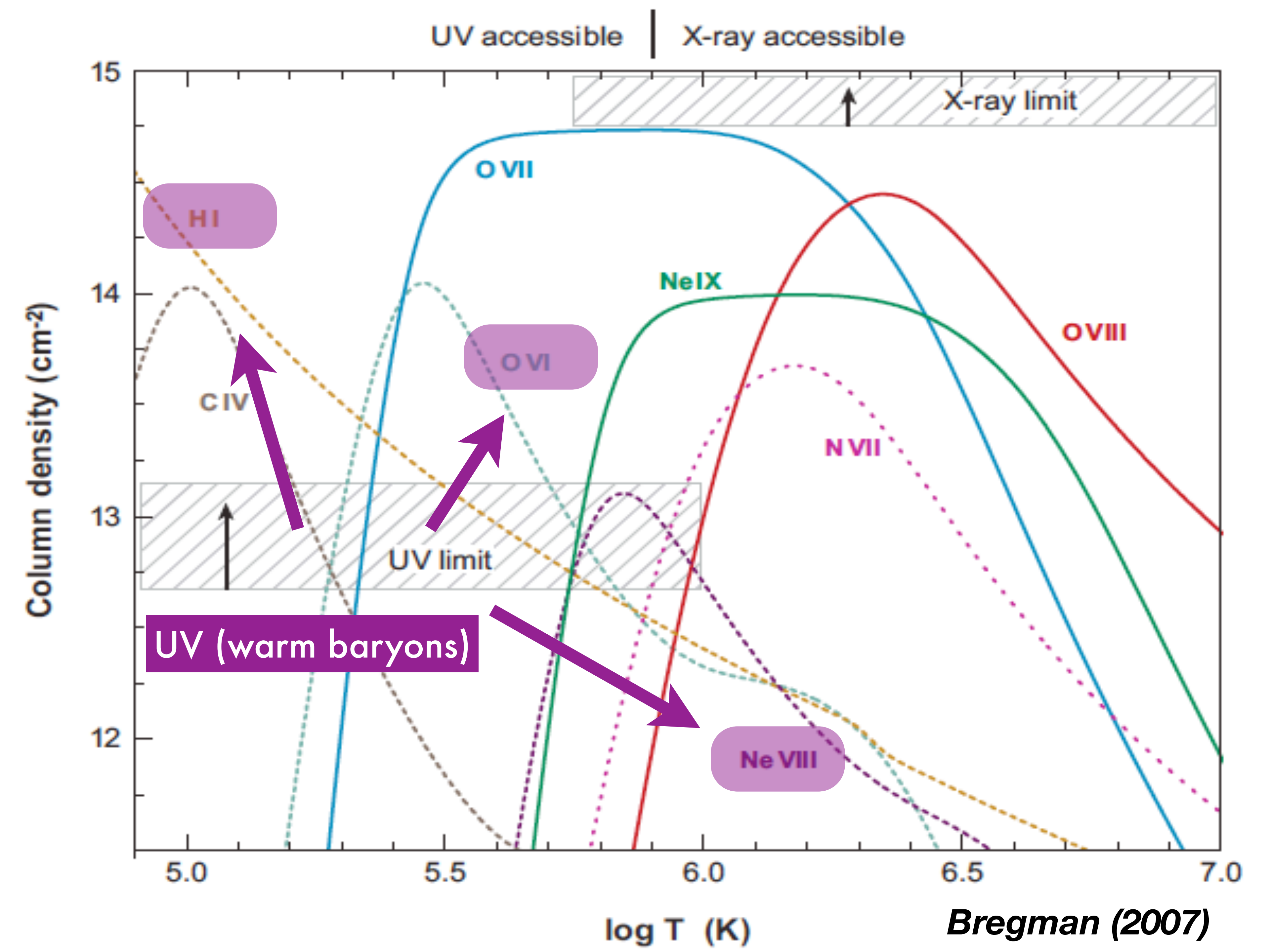
How to detect the warm/hot baryons: UV/X-ray spectroscopy

Absorption	***Imaging***
Depend on background sources	No dependency on background sources
Sensitive to density	Sensitive to density square
No dependency on the XRB	Removal of the XRB

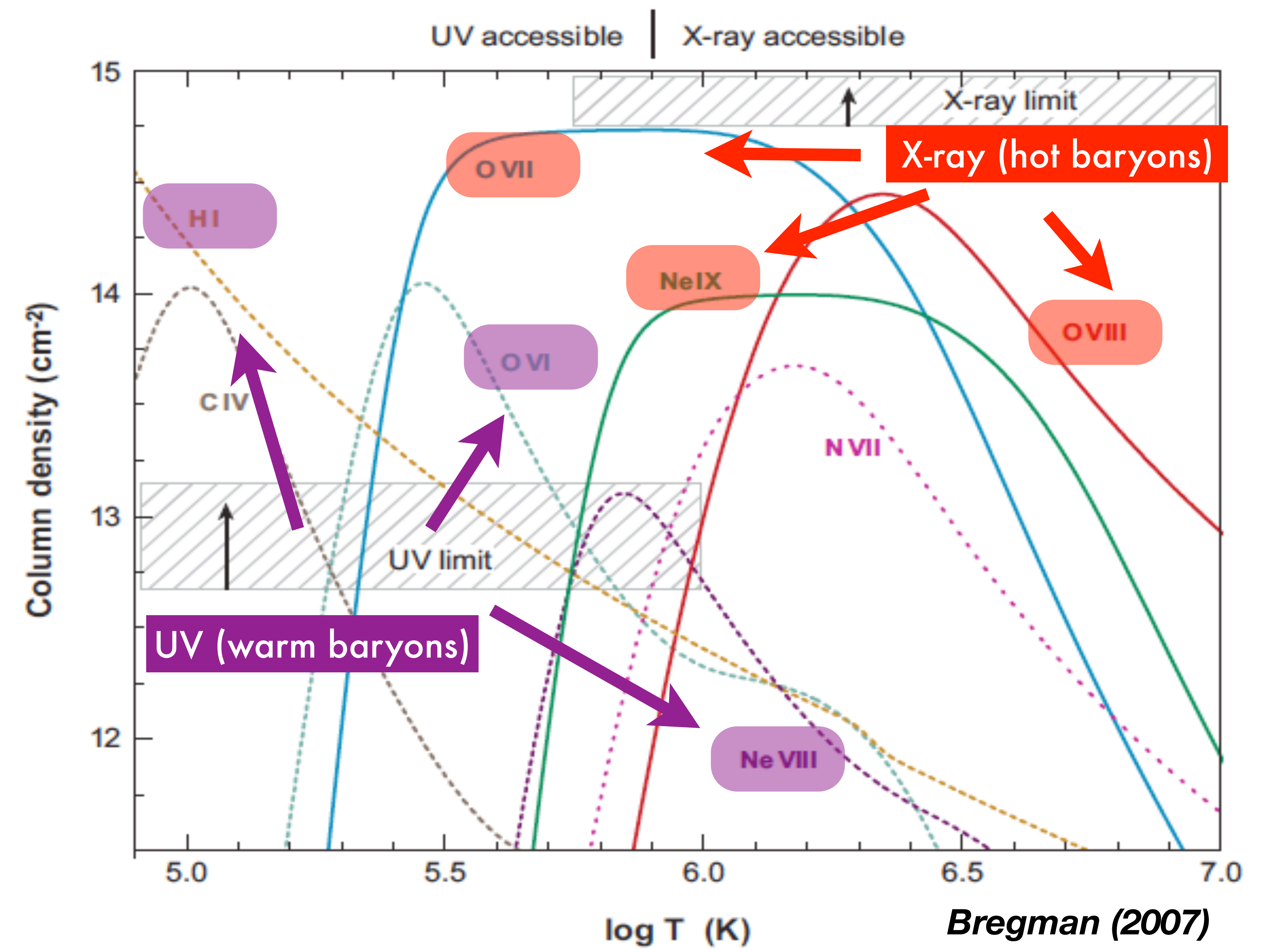
Ultraviolet	***X-ray***
H I, O VI, C IV, etc	O VII, O VIII, C V, Ne X, etc
Plasma with $T \sim 10^5$-10^6 K	Plasma with $T > 10^6$ K



Bregman (2007)



UV accessible
X-ray accessible
X-ray limit
O VII
H I
Ne IX
O VIII
C IV
O VI
N VII
UV limit
UV (warm baryons)
Ne VIII
Column density (cm-2)
15
14
13
12
5.0
5.5
6.0
6.5
7.0
log T (K)
Bregman (2007)


UV accessible
X-ray accessible
X-ray limit
X-ray (hot baryons)
O VII
H I
Ne IX
O VIII
O VI
C IV
N VII
UV limit
UV (warm baryons)
Ne VIII
Column density (cm⁻²)
15
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5.0
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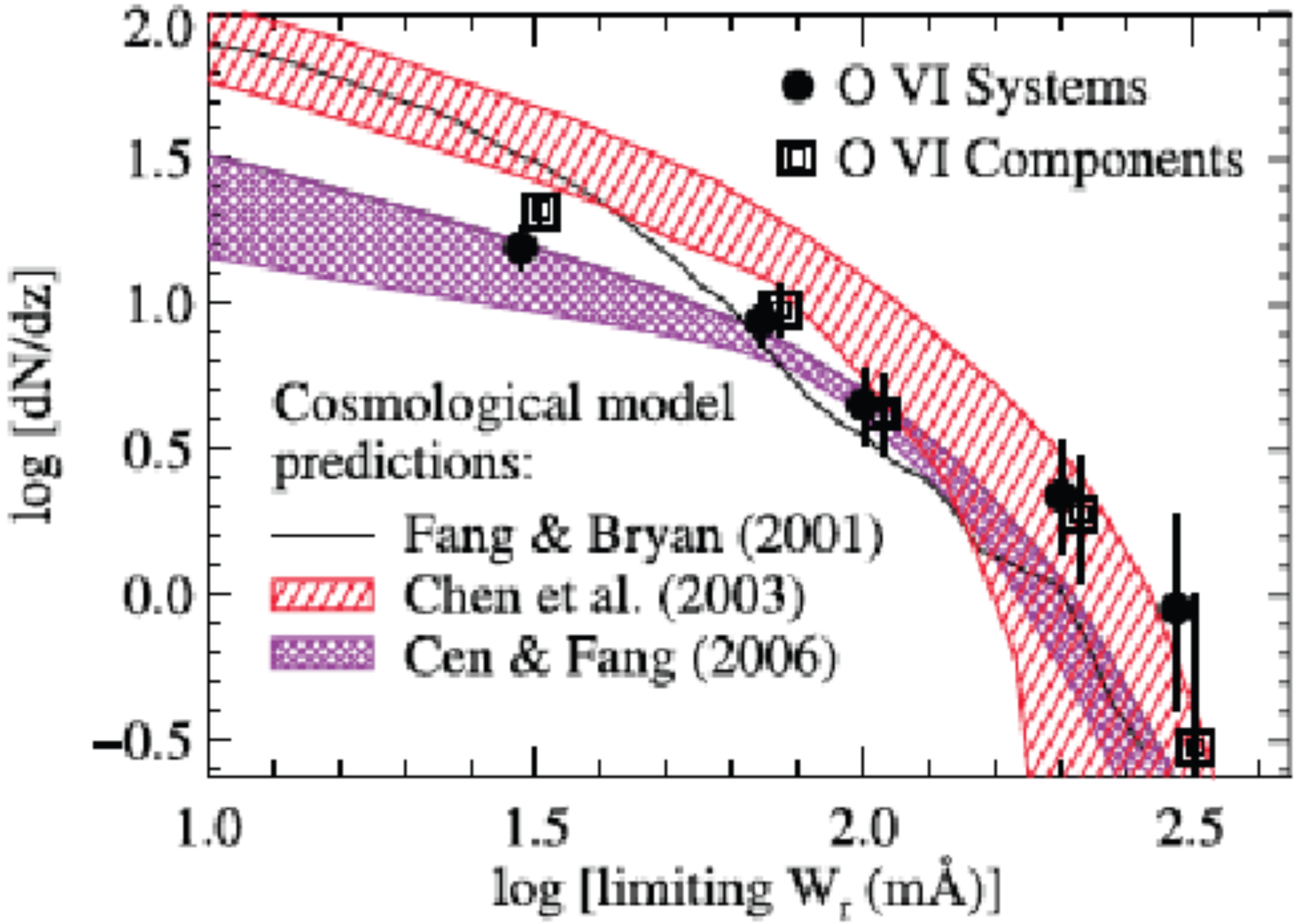
log T (K)
Bregman (2007)

- **Warm baryons, as revealed by OVI-absorption systems**

  ➡ **Challenges to our current theory of galaxy formation and evolution**

- **Hot baryons, as revealed by OVII, OVIII-absorption systems**

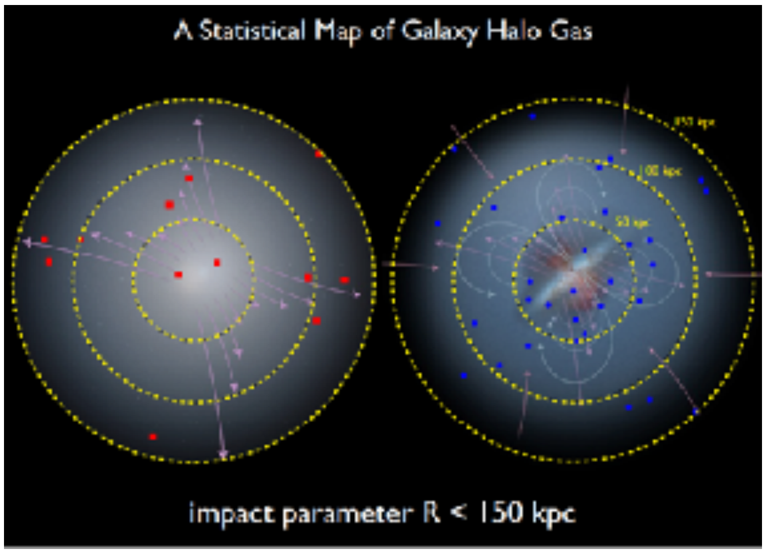
  ➡ **Where are they?**



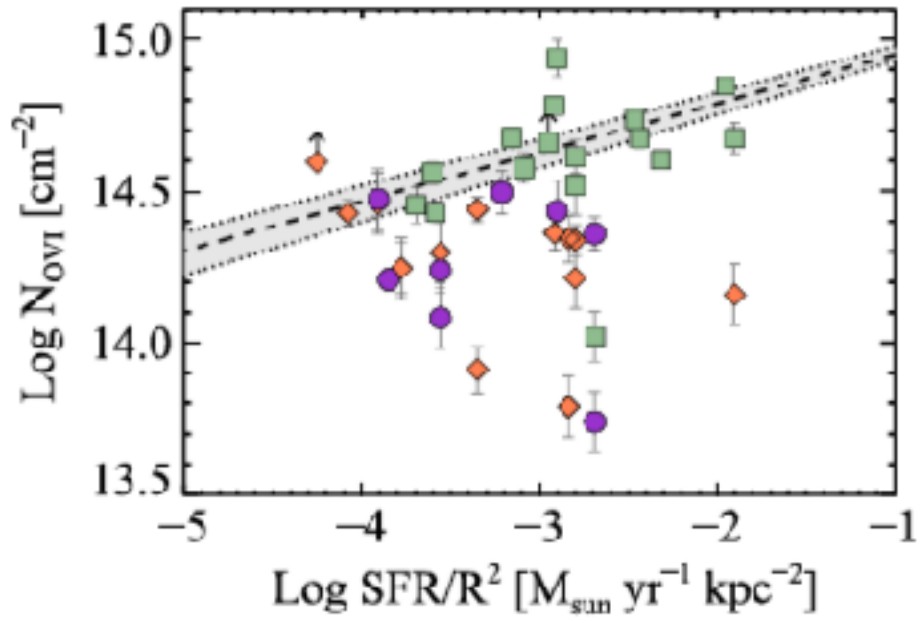
Tripp+2008

- **The observed distribution of the OVI systems is in general consistent with cosmological simulations**
- **A significant amount of the “missing baryons” in the warm phase have been found!**

COS-halo survey:
OVI in the distant halo vs. star formation in the disk?

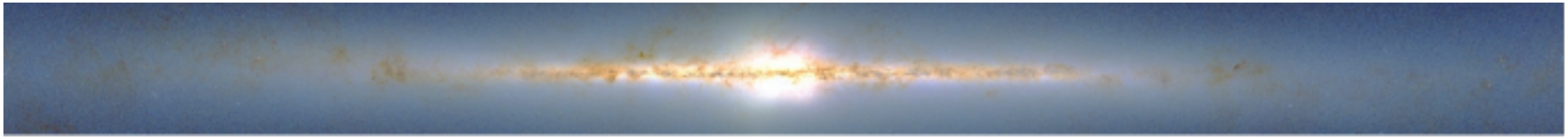


Tumlinson et al. (2011)



Werk et al. (2016)

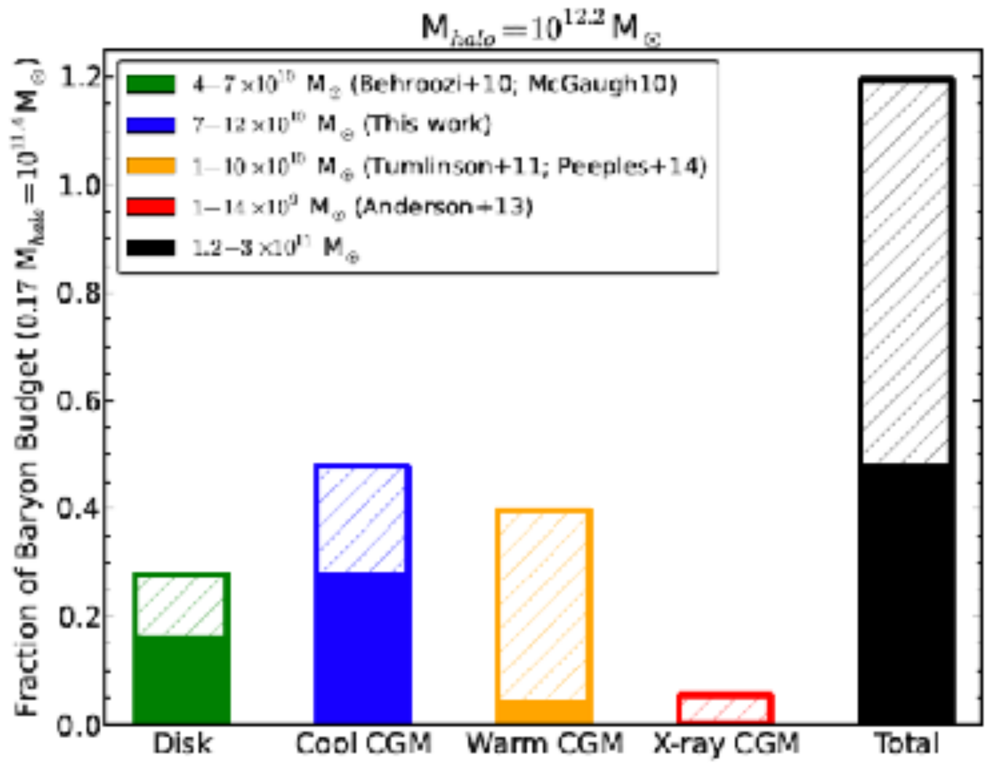
- COS-halo survey: Studying the OVI absorption in the foreground galaxies
- The correlation between the OVI line at the distant halo and the star formation activities in the disk



How can a tiny disk have impact on the distant halo?

Too much warm gas in the CGM?

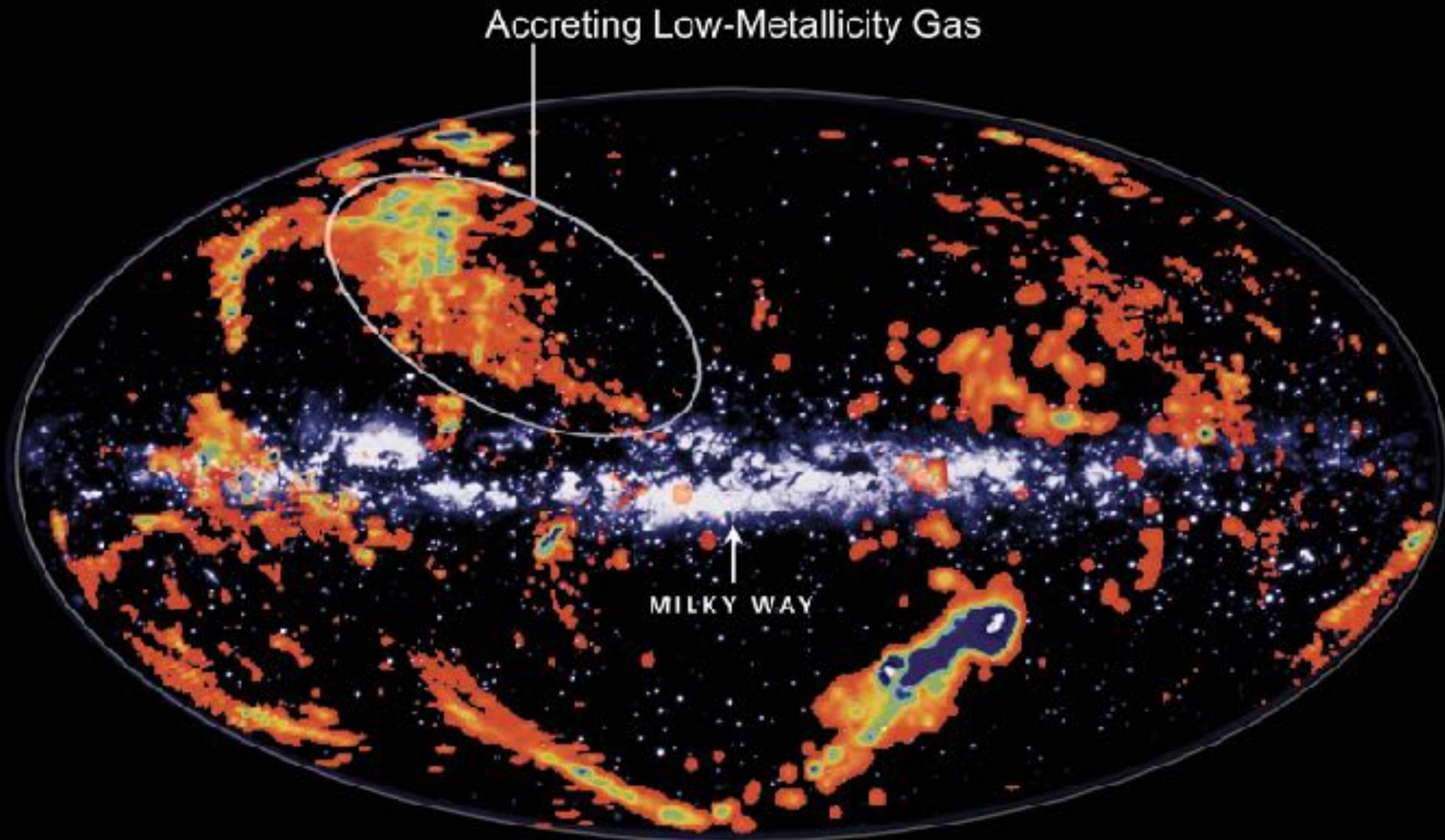
- A "ballpark" estimation of the baryons in galaxies
- Disk: stars and gas in the disk, 15-25%
- Cool CGM: 25-45%
- Warm CGM: 5-40%
- X-ray CGM: < 5%
- Total: 45 - 115%



Werk+2014

The uniform covering fraction of the OVI-system may suggest a diffuse distribution of the warm gas!

Is our Milky Way special?



NASA and B. Wakker (University of Wisconsin-Madison) • STScI-PRC99-46

To summarize, a significant amount of warm baryons have been found in the form of the OVI-absorption systems

However, we do not understand (yet):

- **Why do the distant OVI-systems correlate with star formation activities in the disk?**
- **How do they even get there, assuming OVI were produced in the disk?**
- **What are their spatial distribution, diffuse or discrete clouds?**
- **How do they maintain their ionization status?**

Hot Baryons: X-RAY ABSORPTION OF THE WHIM

Q 0836+710	*Fang+2001*	Chandra HETG	No detection
PKS 2149-306	*Fang+2001*	Chandra HETG	No detection
PKS 2155-304	*Fang+2002*	Chandra LETG	OVIII, > 3σ
H 1821+643	*Fang+2002*	Chandra HETG	No detection
H 1821+643	*Mathur+2003*	Chandra LETG	OVII, < 3σ
3C 120	*McKernan+2003*	Chandra HETG	≥ 3σ
LBQS 1228+1116	*Fujimoto+2004*	XMM RGS	< 3σ
Mkn 421	*Nicastro+2005*	Chandra LETG	???
X Comae	*Takei+2007*	XMM RGS	< 3σ
PKS 0558-504	*Nicastro+2010*	XMM RGS	2.4σ
H 2356-309	*Fang+2010*	XMM, Chandra	4σ
PG 1116+215	*Bonamente+2016*	Chandra LETG	5.2σ
1ES 1553+113	*Nicastro+2018*	XMM RGS	4-5σ

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Bremsstrahlung radiation, emission $\propto$ density square; and absorption $\propto$ density

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Gas Density
Bremsstrahlung radiation, emission $\propto$ density square; and absorption $\propto$ density

Gas Metallicity
Major spectral features come from metals, and we don’t understand metals in the IGM: where, when and how?

Issues with X-ray Absorption Study

- **Typically single line detection (unlike the doublet seeing in UV)!- very difficult to identify!**

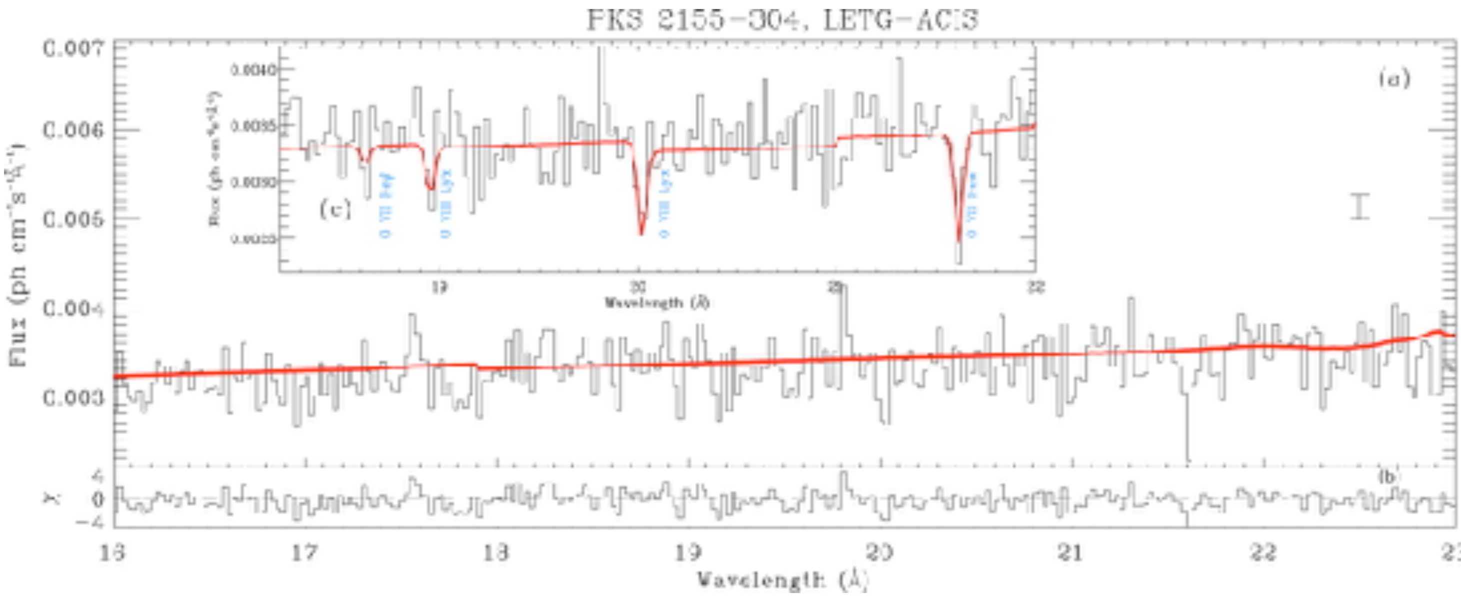
- **Inconsistency between instruments**

- **Distinguishing between an IGM or ISM origins**

- **Statistics: the statistics of a single line is lower when there is no known *"priori"* (difficult for blind search)**

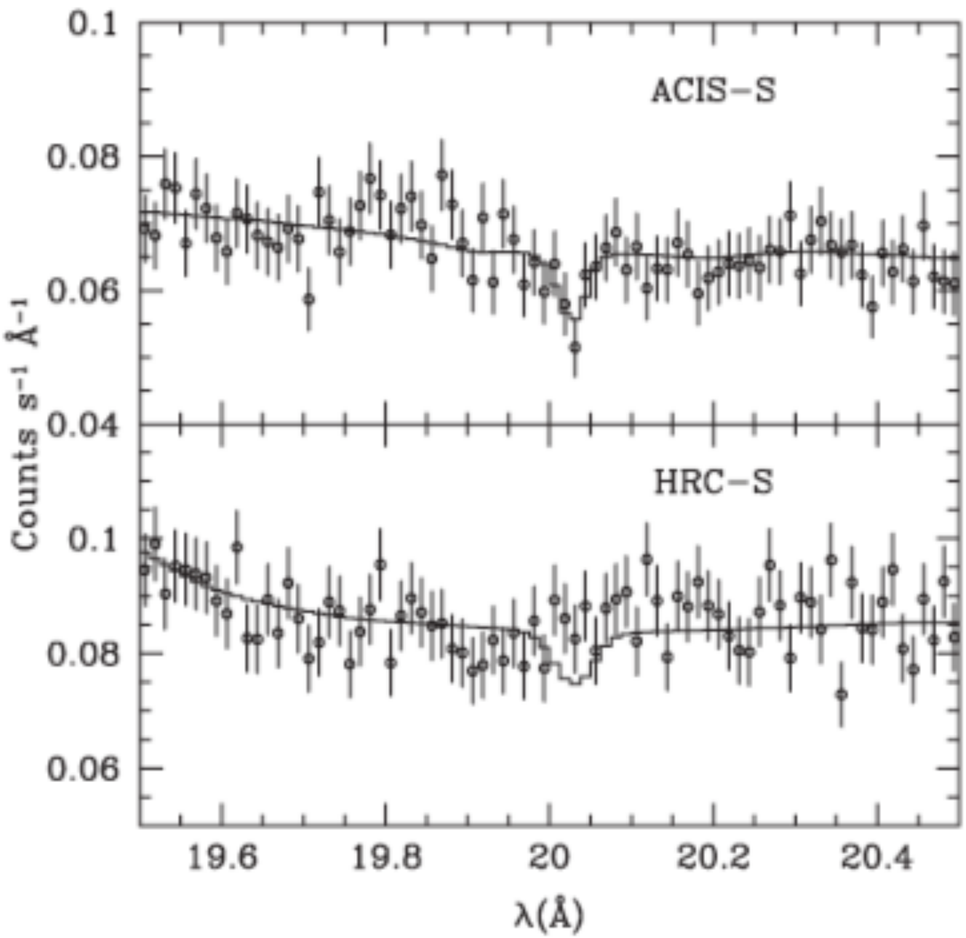
- **Pushing toward the limit of current instruments (1.8 million-second in *Nicastro+2018*)!**

Case study: PKS 2155-304



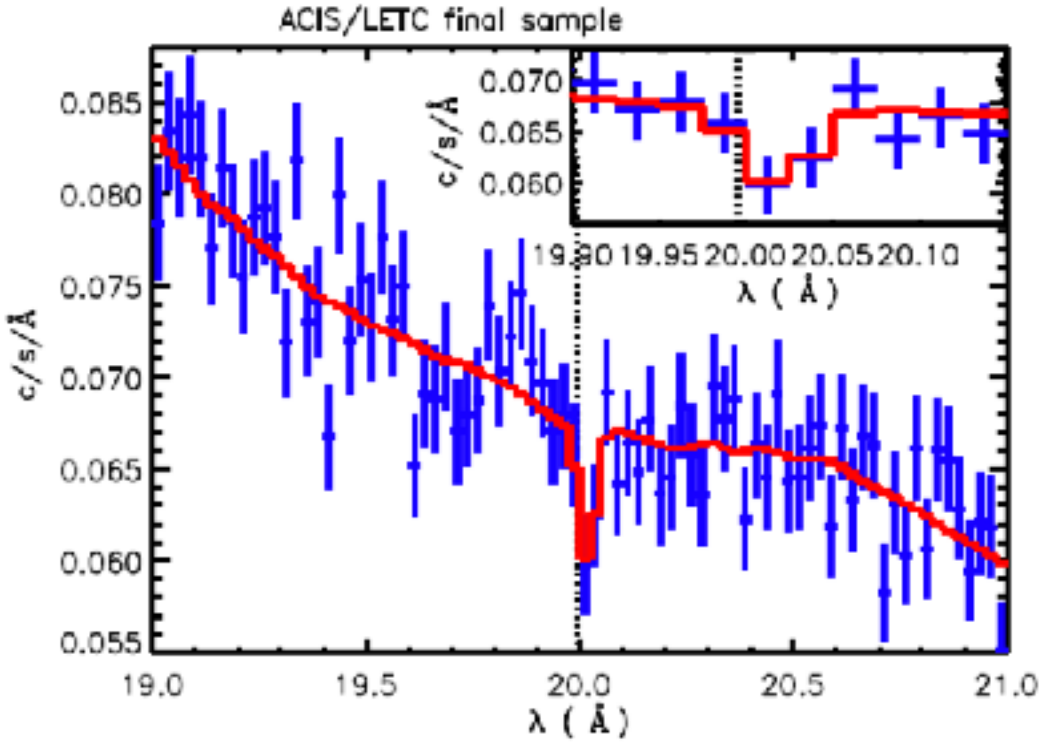
Fang+2003

- **Detection of an intergalactic OVIII absorption line in the X-ray spectrum of PKS 2155-304 with Chandra LETG+ACIS (85 ksec exposure time)**
- **However, *no detection* with Chandra LETG+HRC, and XMM RGS**



Williams+2007

- ***Williams+2007*: clear detection of this line in Chandra LETG+ACIS observations (~ 250 ksec expo. time)**
- **Still, *no detection* with Chandra LETG+HRC**

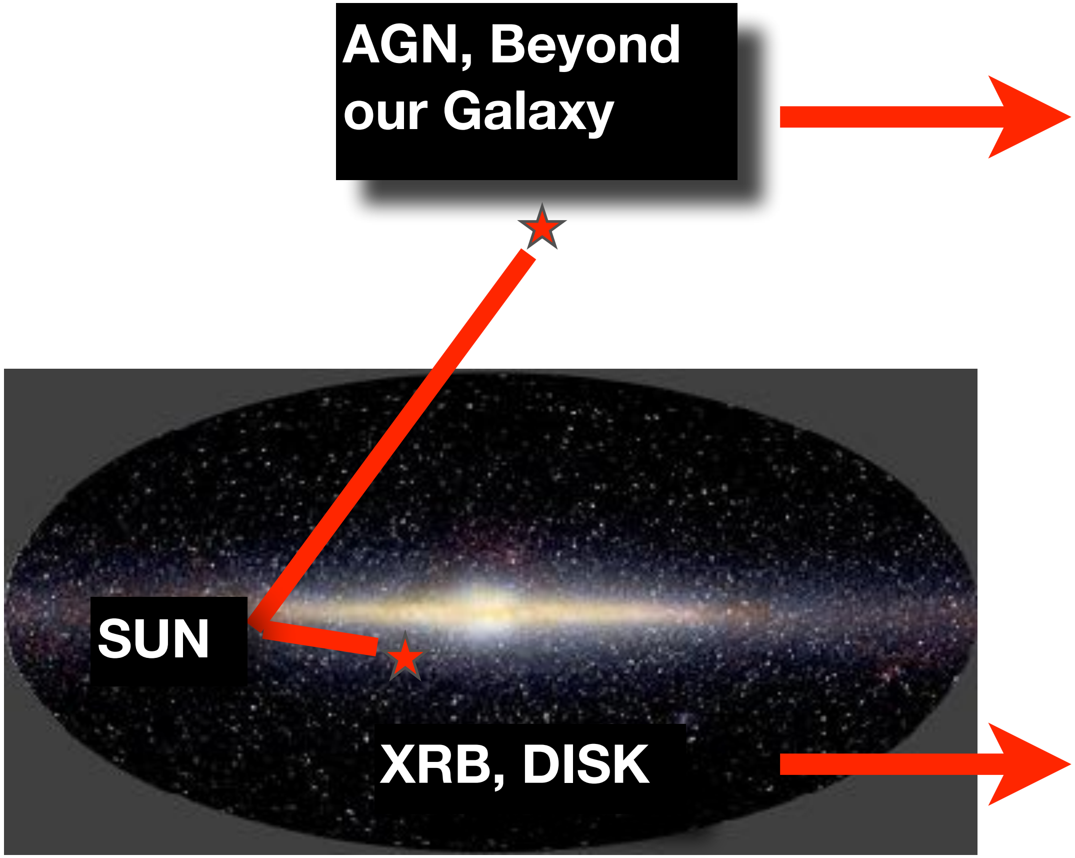


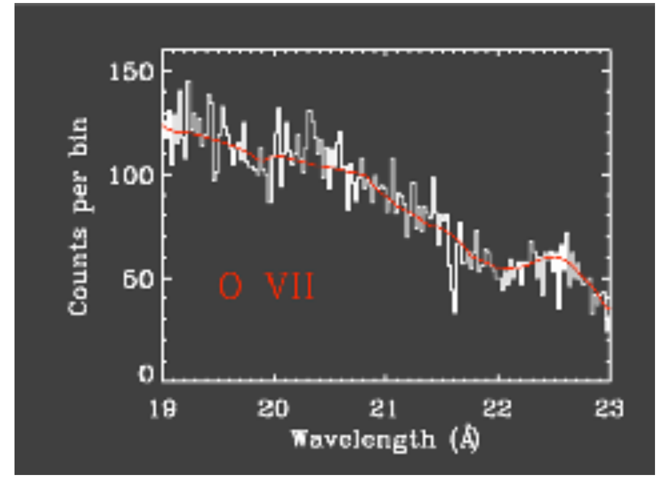
Nevalainen+2018 (in prep.)

- ***Nevalainen+2018*: again, clear detection of this line in Chandra LETG+ACIS observations (~ 870 ksec expo. time)**
- **This line was visible in both +/-1 orders!**
- **Still, *no detection* with Chandra LETG+HRC, and RGS**

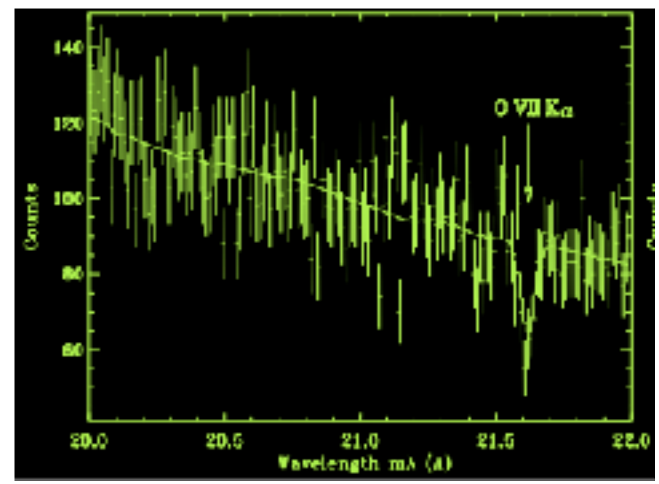
So, why the X-ray absorption so difficult to detect? (in sharp contrast to the numerous detections in our Milky Way)?

- **Is this result consistent with cosmological simulations?**
- **Or, the distribution of the intervening X-ray absorption systems has a much smaller cross-section?**





Fang et al. (2003)



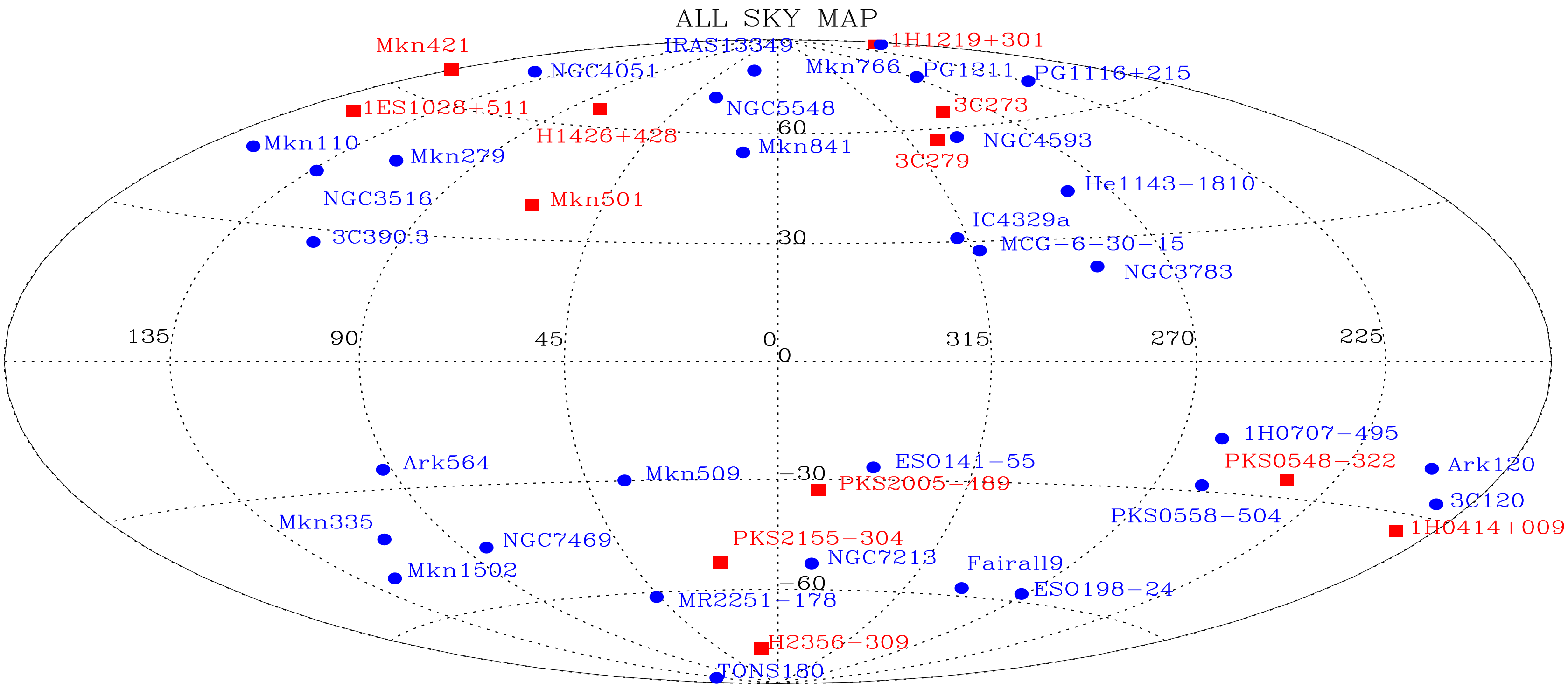
Yao et al. (2005)

- **To test this, we studied the hot gas in our Milky Way, as presented in the X-ray absorption**
- **Using AGNs and X-ray binaries as background sources**
- **Understand the difference between these two “populations” of absorbers**

XMM-Newton Survey of Extragalactic Targets

43 extragalactic sources, 13.5 million seconds

12 BL Lacs, 31 Seyfert 1 galaxies

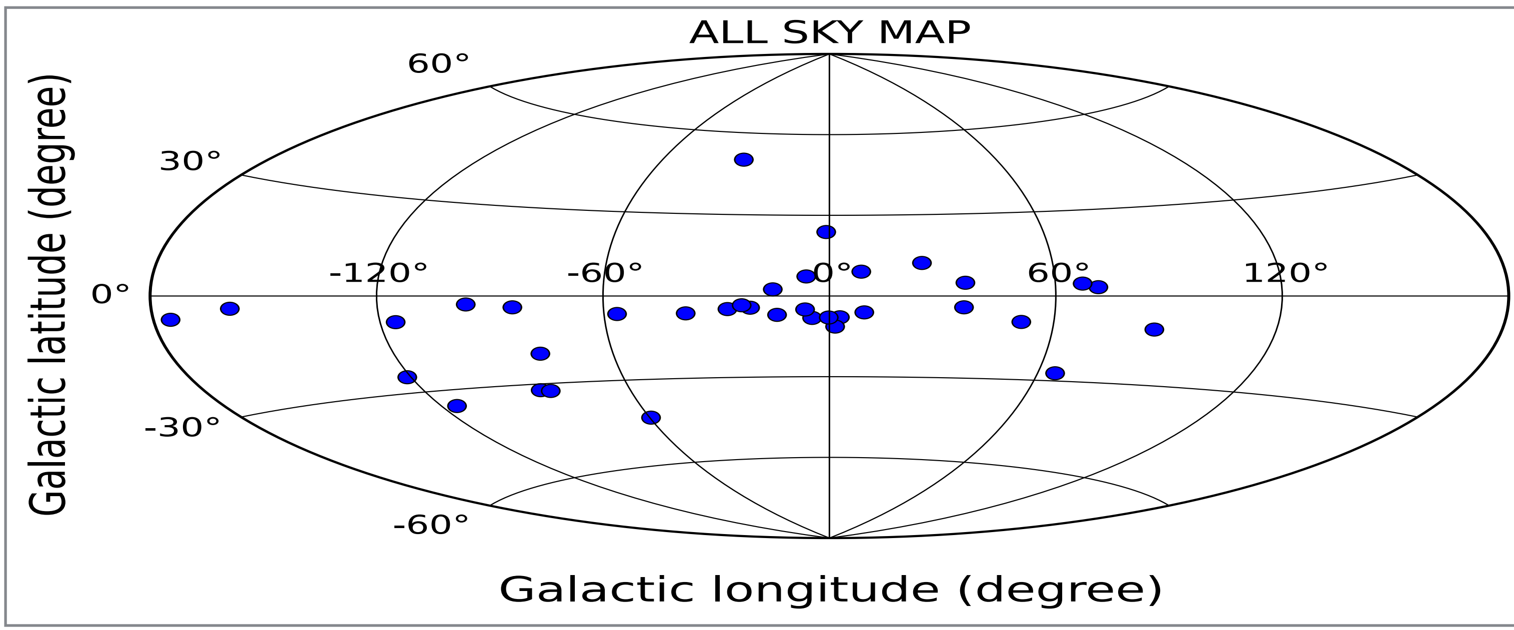


Fang+2015

XMM-Newton Survey of Galactic Targets

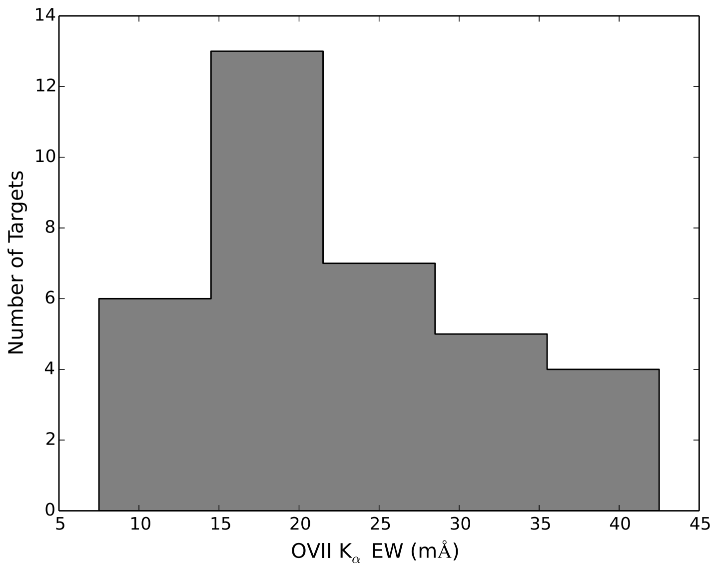
36 Galactic X-ray targets

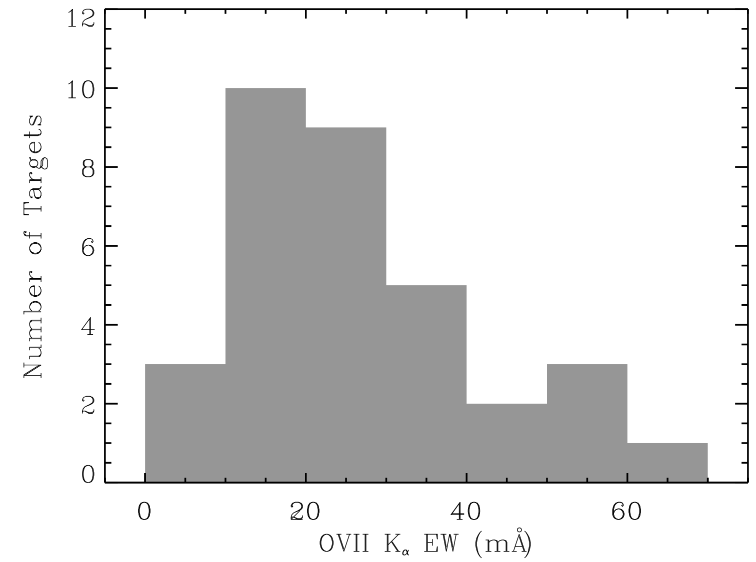
28 low mass X-ray binaries, 4 high mass X-ray binaries, 3 neutron stars, and one nova



Luo+2017

Equivalent Width Distribution of the OVII Kα Line



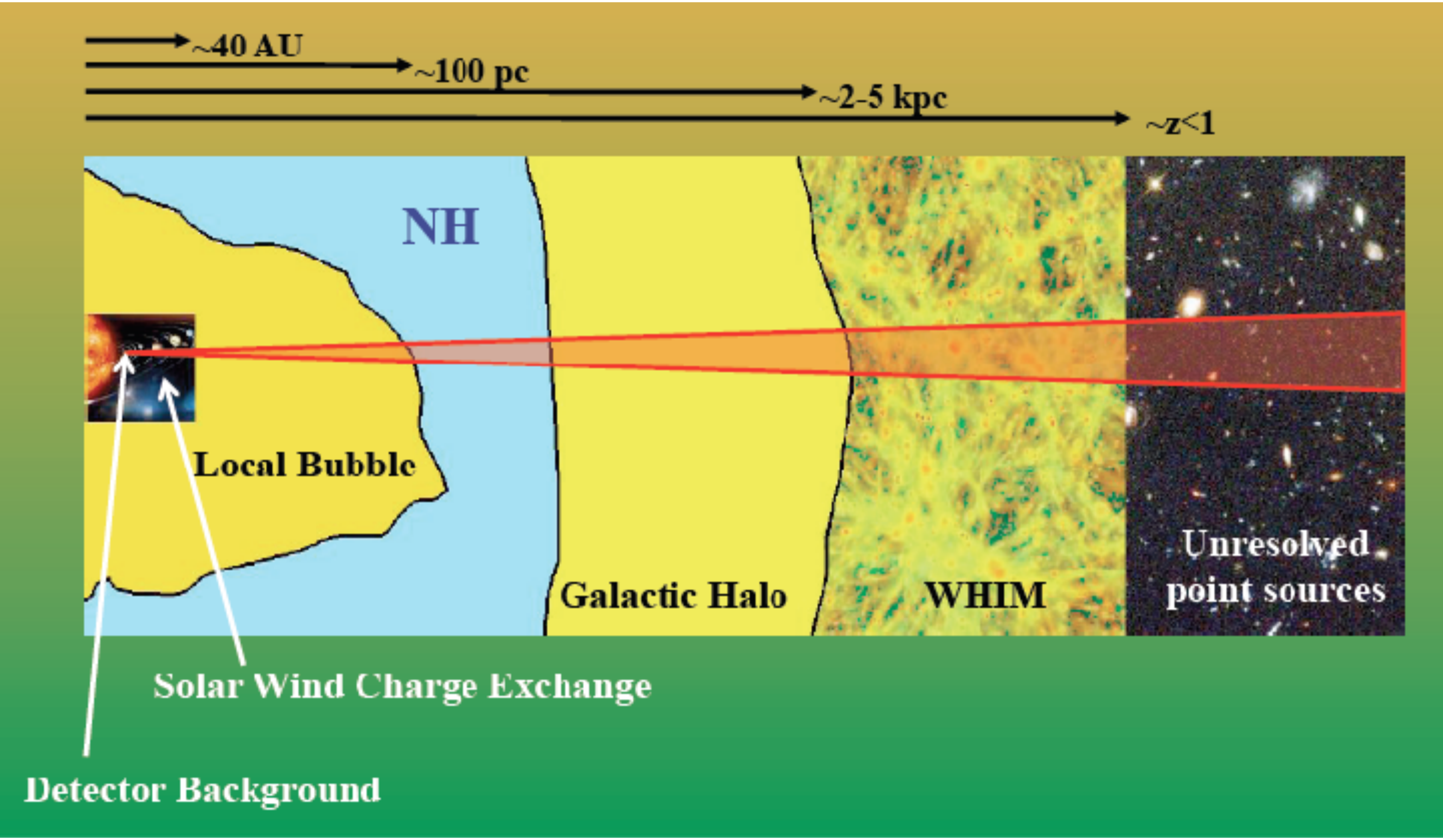


Galactic **Extragalactic**

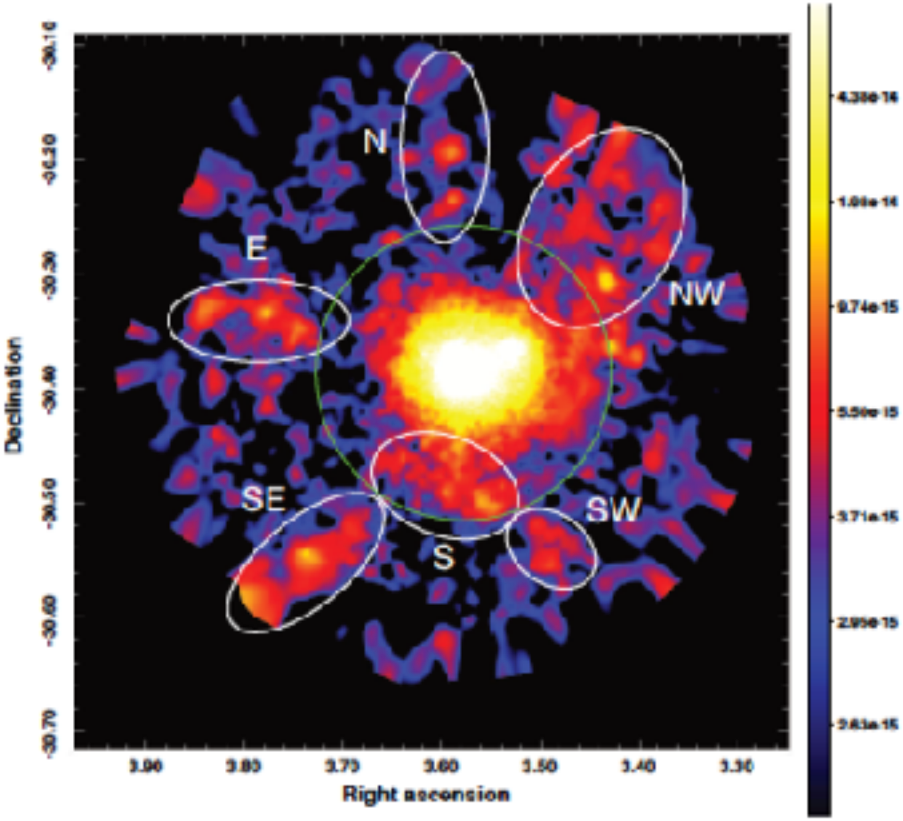
Very similar distribution, with peaks around 20 mA!

Fang+2015, Luo+2017

X-ray Probe of the WHIM: Emission



Galeazzi (2008)

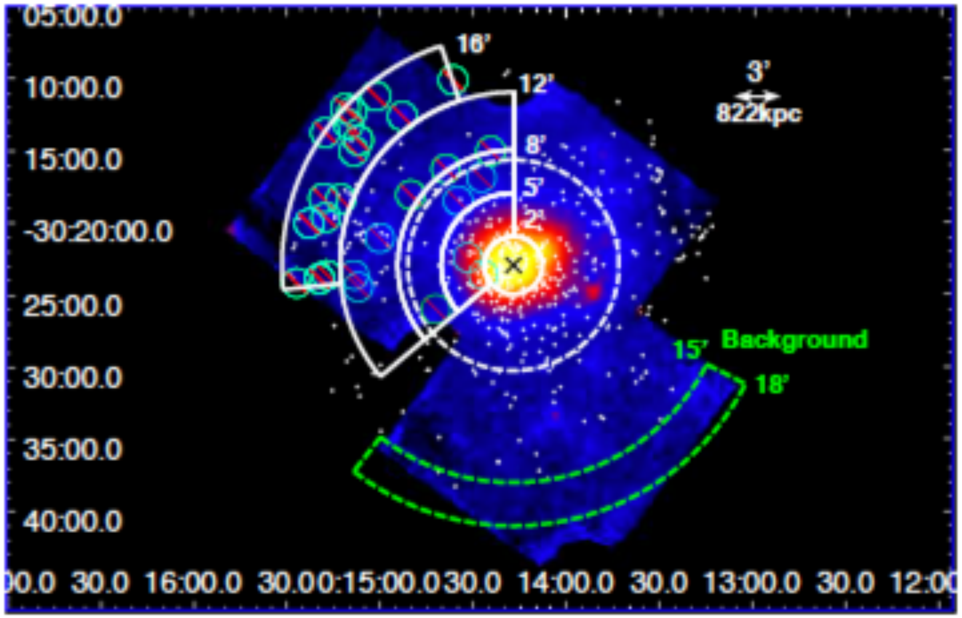


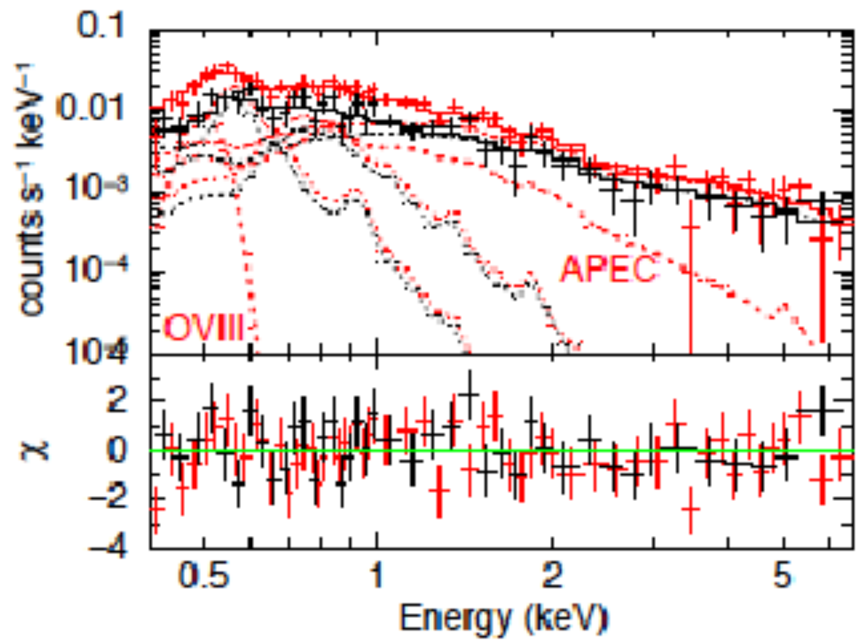
- **XMM-Newton observation of galaxy cluster Abell 2744**
- **Hot gas structures that are coherent over scales of 8 Mpc**
- **Warm-hot baryons comprise 5-10 per cent of filaments in the cosmic web**

Eckert et al. (2015)

Region	$\langle z \rangle$	T [10^6 K]	M_{gas} [$h_{70}^{-1} M_\odot$]	S/N X-ray	M_{tot} [$h_{70}^{-1} M_\odot$]	S/N lensing	f_{gas}
E	0.308	15 ± 2	$(3.8 \pm 0.6) \times 10^{12}$	15.4	$(7.9 \pm 2.8) \times 10^{13}$	3.1	0.05 ± 0.02
S	0.303	16 ± 2	$(7.1 \pm 0.8) \times 10^{12}$	22.6	$(9.5 \pm 2.4) \times 10^{13}$	6.8	0.07 ± 0.02
SW	0.305	8^{+4}_{-2}	$(2.0 \pm 0.4) \times 10^{12}$	9.6	$(4.8 \pm 1.7) \times 10^{13}$	3.1	0.04 ± 0.02
NW1	0.305	25 ± 4	$(5.7 \pm 0.3) \times 10^{12}$	25.3	$(9.5 \pm 2.7) \times 10^{13}$	5.2	0.06 ± 0.02
NW2	0.305	19 ± 2	$(1.9 \pm 0.1) \times 10^{13}$	25.9	$(1.2 \pm 0.3) \times 10^{14}$	3.3	0.15 ± 0.04

Search for WHIM around A2744 using Suzaku





Hattor+2017

- Spectral fit significantly (99.2 % significance) improved when OVII and OVIII lines are included in the spectral model.

Other potential probes of the hot baryons

- **Fast radio burst?**

$$DM = \int_0^D n_e(l)dl$$

- **Sunyaev-Zel'dovich effect (thermal and kinetic): the distortion of the cosmic microwave background radiation (CMB) through inverse Compton scattering by thermal and kinematic motion of electrons**

- **Warm baryons, as revealed by OVI-absorption systems**
  ➡ **Challenges to our current theory of galaxy formation and evolution**

- **Hot baryons, as revealed by OVII, OVIII-absorption/ emission systems**
  ➡ **Where are they?**

- **Looking forward ...**
  ➡ **Instrumentation development**
  ➡ **Numerical simulation: sub-grid physics?**